



A propelling neutron star in the enigmatic Be-star γ Cassiopeia

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Accepted 2016 October 27. Received 2016 October 18; in original form 2016 September 27; Editorial Decision 2016 October 18

ABSTRACT

γ Cassiopeia (γ Cas), is known to be a binary system consisting of a Be-type star and a low-mass ($M \sim 1 M_{\odot}$) companion of unknown nature orbiting in the Be-disc plane. Here, we apply the quasi-spherical accretion theory on to a compact magnetized star and show that if the low-mass companion of γ Cas is a fast spinning neutron star, the key observational signatures of γ Cas are remarkably well reproduced. Direct accretion on to this fast rotating neutron star is impeded by the propeller mechanism. In this case, around the neutron star magnetosphere a hot shell is formed which emits thermal X-rays in qualitative and quantitative agreement with observed properties of the X-ray emission from γ Cas. We suggest that γ Cas and its analogues constitute a new subclass of Be-type X-ray binaries hosting rapidly rotating neutron stars formed in supernova explosions with small kicks. The subsequent evolutionary stage of γ Cas and its analogues should be the X Per-type binaries comprising low-luminosity slowly rotating X-ray pulsars. The model explains the enigmatic X-ray emission from γ Cas, and also establishes evolutionary connections between various types of rotating magnetized neutron stars in Be-binaries.

Key words: stars: emission-line, Be – stars: neutron.

1 INTRODUCTION

The optically brightest Be-star γ Cassiopeia (γ Cas) (B0.5IVpe) is a well-known binary system which consists of an optical star with mass $M_{\text{Be}} \approx 16 M_{\odot}$ and an unseen hot companion with mass $M_{\text{X}} \approx 1 M_{\odot}$. The binary orbital plane and the disc of the Be-star are coplanar (Harmanec et al. 2000; Miroshnichenko, Bjorkman & Krugov 2002; Gies et al. 2007). Since the discovery of X-ray emission from γ Cas 50 years ago (Mason, White & Sanford 1976), its enigmatic properties attracted large attention, but so far have remained unexplained (see a recent review by Smith, Lopes de Oliveira & Motch 2016).

γ Cas is a prototype of a class of Be-stars which have X-ray luminosities of 10^{32} – 10^{33} erg s^{−1}, which is intermediate between those usually observed from B-stars with similar spectral types and those of X-ray and cataclysmic variable binaries. The defining feature of X-ray emission from the class of γ Cas analogues is a very hot thermal spectrum with $T \gtrsim 100$ MK (or $kT \gtrsim 10$ keV) and the presence of the fluorescent Fe K line. No X-ray pulsations have been detected in γ Cas analogues.

After γ Cas was detected in X-rays, the idea of an accreting neutron star (NS) companion had been put forward (White et al. 1982) based on the apparent similarity between the X-ray spectra of γ Cas and the Be X-ray binary (BeXRB) X Per which hosts an NS. How-

ever, the subsequent accumulation and analysis of high-quality multiwavelength observations of γ Cas revealed major difficulties for this model. Corbet (1996) raised the possibility of magnetospheric accretion in γ Cas. Lopes de Oliveira et al. (2006) pointed out that direct accretion on to an NS is unlikely because the observed X-ray luminosity of γ Cas (B0.5IVe+NS?, $P_{\text{orb}} \approx 204$ day, $e \lesssim 0.03$) would be much lower than that in X Per (O9.5III-IVe+NS, $P_{\text{orb}} \approx 250$ day, $e \approx 0.1$). It was also pointed out that the Fe K line is usually not seen in the X-ray spectra of long-period BeXRBs while it is observed in γ Cas. Moreover, a non-thermal spectral component is typically present in X-ray spectra of BeXRBs, but is absent in γ Cas.

Despite large discussion in the literature, to our knowledge no quantitative model predicting the observed properties of γ Cas exists so far. In this letter, we derive quantitative predictions of X-ray emission from an NS in the propeller regime embedded in a hot quasi-spherical shell and compare them with observed properties of γ Cas.

The good agreement between our model and observations lends credence to the proposed model and allows us to suggest an evolutionary scenario for γ Cas and its analogues. In our new scenario, these objects represent natural evolutionary stage of binary X-ray systems which experienced mass exchange in the past, suffered only a small kick during supernova (SN) explosion of the primary and will evolve to accreting BeXRBs, such as X Per, in the future.

The formation of X Per in the context of the standard evolutionary scenario for BeXRBs was considered by Delgado-Martí et al.

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(2001). They found that the formation of this Be+NS system likely involved a quasi-stable and nearly conservative transfer of mass from the primary to the secondary. It was suggested that the final mass of He star remnant of the primary was less than $6 M_\odot$ and suggested that its SN explosion might have been completely symmetric. Shtykovskiy & Gilfanov (2005) studied the population of compact X-ray sources in the Large Magellanic Cloud, and included the propeller effect to explain the observed X-ray luminosity distribution.

In this letter, we expand the standard approach to the high-mass X-ray binary evolution (e.g. Pfahl et al. 2002) by showing that the quasi-spherical accretion in young BeXRBs may be impeded.

2 PROPELLER EFFECT

NSs are born in core collapses of massive stars. NSs have masses of $0.8 M_\odot \lesssim M_X \lesssim 2.5 M_\odot$ (Lattimer & Prakash 2007), initially short spin periods $P_0^* \sim 10\text{--}100$ ms and are strongly magnetized with the characteristic dipole magnetic moment $\mu_{30} = \mu / (10^{30} \text{ G cm}^3) \sim 1$ (e.g. Popov & Turolla 2012).

Some NSs are found in binary systems with a high-mass stellar companion of OB or Be spectral type. The OB-stars lose mass via their radiatively driven winds, and rapidly rotating Be-stars also possess decretion discs (Porter & Rivinius 2003; Reig 2011). In the standard formation model of high-mass X-ray binaries, an NS gravitationally attracts the wind matter outflowing from its early-type companion within the Bondi radius

$$R_B = 2GM_X/v_0^2, \quad (1)$$

where v_0 is the NS velocity relative to the wind (van den Heuvel & Heise 1972; Tutukov, Yungelson & Klayman 1973). If the specific angular momentum of the gravitationally captured matter is small, the accretion flow is quasi-spherical. An NS with radius $R_0 \approx 10^6$ cm and accreting matter with density ρ at the rate $\dot{M}_B \approx \pi \rho v_0 R_B^2$ could gravitationally sustain a luminosity $GM\dot{M}_B/R_0 \sim 0.1 \dot{M}_B c^2$ (where c is the speed of light). Hence, if all gravitationally captured matter were able to reach the NS surface, a bright X-ray source would appear.

However, for matter to reach the NS surface, it should penetrate through its magnetosphere with the characteristic radius $R_A \sim 10^8\text{--}10^9$ cm, defined by the pressure balance between the ambient matter and the magnetic field (see equation 7). Besides the magnetospheric barrier, the centrifugal barrier can also prevent the matter accretion. The rigidly rotating NS magnetosphere reaches a Keplerian velocity at the distance $R_c = (GM(P^*)^2/4\pi^2)^{1/3}$, where P^* is the NS spin period. Only when the condition $R_c \leq R_A$ is met the accretion can start. The corresponding NS spin period is then $P_A^* \approx 17(R_A/10^9 \text{ cm})^{3/2}$ s. If $R_A > R_c$ or, equivalently, $P^* < P_A$, the centrifugal barrier at the magnetospheric boundary would prevent matter accretion (Illarionov & Sunyaev 1975; Stella, White & Rosner 1986). Such situation is referred to as a ‘propeller stage’.

The propeller effect has been suggested to operate at low states of transient X-ray pulsars (Lutovinov et al. 2016; Tsygankov et al. 2016a,b) and has been invoked to explain non-stationary behaviour of supergiant fast X-ray transients (Grebenev & Sunyaev 2007; Bozzo, Falanga & Stella 2008).

3 THE HOT MAGNETOSPHERIC SHELL AND ITS PROPERTIES

In a wind-fed binary system with rapidly rotating NS, the propeller effect has an important difference compared to the one operating in the disc-fed systems. At the propeller stage, the gravitationally

captured material from the stellar wind of the companion will accumulate above R_A to form a hot quasi-spherical shell extending up to $\sim R_B$ (Davies & Pringle 1981; Shakura et al. 2012). The shell can power a gravitational luminosity of

$$L_X \approx GM_X \dot{M}_B / R_A \sim 10^{32} \text{ erg s}^{-1}. \quad (2)$$

To good approximation, the density and temperature distributions in the shell can be found from the hydrostatic equilibrium:

$$\rho(R) = \rho_A (R_A/R)^{3/2}, \quad T(R) = T_A (R_A/R), \quad (3)$$

where ρ_A and T_A are referred to the near-magnetospheric values. The temperature is determined by the condition

$$\mathcal{R}T = \mu_m \frac{\gamma - 1}{\gamma} GM_X \frac{1}{R_A}, \quad (4)$$

where \mathcal{R} is the universal gas constant, μ_m is the molecular weight and γ is adiabatic index of the gas. In the following, we will assume $\mu_m = 0.5$ and $\gamma = 5/3$. The magnetospheric radius is determined from the pressure balance at the magnetospheric boundary:

$$K_2 (B_0^2/8\pi)(R_0/R_A)^6 = \rho_A \mathcal{R}T_A = \rho_A (2/5)(GM_X/R_A), \quad (5)$$

where the factor $K_2 \approx 7.56$ takes into account compression of a quasi-spherical magnetosphere (Arons & Lea 1976). The total X-ray luminosity of the shell due to bremsstrahlung cooling is

$$L_X = \int_{R_A}^{R_B} \epsilon_{\text{br}} 4\pi r^2 dr = \frac{4\pi K_{\text{br}}}{\sqrt{\mathcal{R}}} \rho_A^2 \sqrt{\frac{2}{5}} \frac{GM_X}{R_A} \frac{R_A^3}{2} \left(1 - \frac{1}{\sqrt{R_B/R_A}}\right), \quad (6)$$

where we have used $\epsilon_{\text{br}} = K_{\text{br}} \rho^2 \sqrt{T}$ and the scaling laws for the density and temperature in the shell given by equation (3). The last term in the parentheses can be neglected since usually $R_B/R_A \gg 1$. For a given L_X and NS magnetic field $\mu = B_0 R_0^3/2$, equations (5) and (6) can be solved to give

$$R_A \simeq 7.6 \times 10^8 [\text{cm}] \mu_{30}^{8/15} L_{32}^{-2/15} (M_X/M_\odot)^{-4/15}, \quad (7)$$

where $L_{32} = L_X/(10^{32} \text{ erg s}^{-1})$,

$$\rho_A \approx 4.4 \times 10^{-11} [\text{g cm}^{-3}] (L_{32}/\mu_{30})^{2/3} (M_X/M_\odot)^{1/3} \quad (8)$$

and the electron number density:

$$n_{e,A} \approx 2.6 \times 10^{13} [\text{cm}^{-3}] (L_{32}/\mu_{30})^{2/3} (M_X/M_\odot)^{1/3}. \quad (9)$$

The temperature at the shell base is

$$T_A = \frac{2}{5} \frac{GM_X}{\mathcal{R}R_A} \approx 27 [\text{keV}] (R/10^9 [\text{cm}])^{-1} \approx 36 [\text{keV}] \mu_{30}^{-8/15} L_{32}^{2/15} (M_X/M_\odot)^{19/15}. \quad (10)$$

This high temperature justifies the use of bremsstrahlung radiative losses from the shell.

The volume emission measure (EM) of the shell is given by

$$\begin{aligned} \text{EM} &= \int_{R_A}^{R_B} n_e^2(r) 4\pi r^2 dr = 4\pi n_{e,A}^2 R_A^3 \ln \left(\frac{R_B}{R_A} \right) \\ &\approx 3.7 \times 10^{54} [\text{cm}^{-3}] \mu_{30}^{4/15} L_{32}^{14/15} (M_X/M_\odot)^{-2/15} \ln \left(\frac{R_B}{R_A} \right). \end{aligned} \quad (11)$$

In the context of an NS coplanar with the Be-star disc, given the slow equatorial disc wind velocities $v_0 \sim 10^7 \text{ cm s}^{-1}$, we find $R_B/R_A \sim 100$ (see equation 1), and the EM can be $\sim 10^{55} [\text{cm}^{-3}]$ and even higher.

4 EVOLUTION OF THE NS SPIN

The propeller effect can be important in the astrophysical context provided that its duration is sufficiently long compared to the lifetime of the Be-star (several million years). The propeller effect operates only for fast rotating NSs. Therefore, to evaluate for how long accretion may be inhibited and a hot magnetospheric shell can be supported by the wind from the optical star, one should consider the spin evolution of a non-accreting NS.

The transfer of angular momentum in magnetospheric shells around quasi-spherically accreting NSs was considered in more detail by Shakura et al. (2012). It was found, in particular, that in such shells a nearly isomomentum angular velocity distribution is established, $\omega(R) = \omega_m(R_A/R)^2$, where ω_m is angular velocity of matter at the magnetosphere. However, when accretion on to the NS is centrifugally prohibited, the angular momentum transport by viscous forces through the surrounding convective shell leads to the angular velocity distribution $\omega(R) = \omega_m(R_A/R)^{7/4}$ (see appendix A6 in Shakura et al. 2012).

From equations (51) and (52) presented in Shakura et al. (2012), at the stage with no accretion, the braking torque applied to the NS from the surrounding shell is

$$I\dot{\omega}_* = -\frac{49}{4}\omega_B^2 \left(\frac{R_B}{R_A}\right)^{7/2} \pi C \rho_A R_A^5, \quad (12)$$

where I is the NS moment of inertia, $\omega_B = 2\pi/P_{\text{orb}}$ is the binary orbital frequency, $C \gtrsim 1$ is a numerical coefficient which determines turbulent viscosity through the Prandtl law and hence viscous stresses in the convective shell. Plugging into (12) the density distribution in the shell, $\rho_A = \rho_B(R_B/R_A)^{3/2}$, as given by (8) and expressing it through the X-ray luminosity L_X , equation (12) for the braking torque can be rearranged to

$$I\dot{\omega}_* = -49\omega_B^2 R_B^3 C \left(\frac{R_A L_X}{GM_X v_0}\right). \quad (13)$$

The characteristic NS spin-down time in this regime thus becomes

$$t_{\text{sd}} \equiv \frac{I\omega_*}{I\dot{\omega}_*} = \frac{I\omega_*}{49\omega_B^2 R_B^3 C} \left(\frac{GM_X v_0}{R_A L_X}\right) \approx 2 \times 10^5 [\text{yr}] \left(\frac{P_*}{1\text{s}}\right)^{-1} \times \left(\frac{P_{\text{orb}}}{100\text{d}}\right)^2 \left(\frac{v_0}{100\text{km s}^{-1}}\right)^7 \left(\frac{R_A}{10^9\text{cm}}\right)^{-1} L_{32}^{-1} \quad (14)$$

(here the constant C was set to unity.)

As can be seen from equation (14), the NS spin-down time is extremely sensitive to the NS velocity relative to the disc wind (as $\sim v_0^7$) and to binary orbital period (as $\sim P_{\text{orb}}^2$). It can be made much longer than the characteristic spin-down time at the propeller stage during the disc accretion on to the NS with the same magnetospheric radius, $t_{\text{sd,d}} \approx (I\omega_*)(\mu^2/R_A^3)^{-1} \sim 10^5 [\text{yr}] (P_*/1\text{s})^{-1} \mu_{30}^{-2} R_{A,9}^3$.

Given the significant time duration estimated by equation (14), it is obvious that propelling NSs surrounded by hot quasi-spherical shells can be present among low-luminosity non-pulsating high-mass X-ray binaries. Their X-ray spectral properties as summarized in Section 6 and their long orbital binary periods can be used to distinguish them from, for example, faint hard X-ray emission from magnetic cataclysmic variables (e.g. Hong et al. 2016).

5 HEATING OF THE MAGNETOSPHERIC SHELL

In the case of a ‘supersonic propeller’ (Davies & Pringle 1981), additional source of the shell heating is provided by the mechanical energy flux from the spinning-down NS (sometimes referred to as

‘magnetospheric accretion’; see Stella et al. 1986). Multiplication of equation (12) by the angular velocity difference at the magnetospheric boundary, $(\omega_* - \omega_m)$, gives the influx of the mechanical energy into the shell at the propeller stage. Clearly, once $\omega_m \rightarrow \omega_*$ during the NS spin-down, the mechanical energy supply to the shell should vanish. However, even in this case the shell can be kept hot due to the gravitational energy release given by equation (2).

To provide X-ray luminosity at the level $L_X \sim 10^{32} - 10^{33} \text{ erg s}^{-1}$ and assuming $R_A \sim 10^9 \text{ cm}$, the gravitational capture rate of stellar wind matter must be $\dot{M}_B \sim 10^{15} - 10^{16} \text{ g s}^{-1}$ or $10^{-10} - 10^{-11} M_\odot \text{ yr}^{-1}$. Using equations (3) and (8), it can be shown that the wind density at the outer boundary of the shell near R_B is sufficient to provide the required mass accretion rate.

The above estimates are done using simple spherically symmetric considerations, which may be violated in complex regions near R_B . However, it is important to note that the observed X-ray luminosity is mostly determined by the Bondi–Hoyle rate, $\dot{M}_B \sim \rho_B R_B^2 v_0$. Expressing it through the density near the shell base eliminates the ill-known value of the wind velocity:

$$\dot{M}_B \sim (1/4)\pi\rho_B R_B^2 v_0 \simeq (1/4)\pi\rho_A R_A^{3/2} R_B^{1/2} v_0 \approx 6 \times 10^{15} [\text{g s}^{-1}] \mu_{30}^{2/15} L_{32}^{4/5} (M_{\text{NS}}/M_\odot)^{-2/5} \quad (15)$$

(here the factor 1/4 takes into account density jump in the strong shock near R_B). Thus, our basic considerations should not be strongly affected by the complicated flow details at R_B and provide robust first-order estimates.

The radiation cooling time of the hot plasma near the base of the shell is rather short, $t_{\text{cool}} \sim 2 \times 10^{11} [\text{s}] T^{1/2} n_e^{-1} \sim 1000 \text{ s}$. The temperature gradient in the quasi-spherical shell turns out to be superadiabatic (Shakura et al. 2012), indicating the presence of convection. To avoid rapid cooling, the convection should lift up a hot parcel of gas faster than it radiatively cools down, i.e. the condition $t_{\text{cool}} > t_{\text{conv}}$, where $t_{\text{conv}} = R_A/v_{\text{conv}}$ is the characteristic time of convective overturn near the shell base, should be met.

The convective velocity is $v_{\text{conv}} = \epsilon_c c_s$, where $c_s = \gamma \mathcal{R}T$ is the adiabatic sound velocity, $\epsilon_c \leq 1$. Plugging R_A and T_A from equation (7) and equation (10), we obtain for the condition $t_{\text{cool}} > t_{\text{conv}}$

$$(\mu_{30} L_{32})^{2/5} < 115 \epsilon_c (M_X/M_\odot)^{28/15}, \quad (16)$$

which is easily satisfied even for small convective velocities. Convection initiates turbulence and the hot thermal plasma in the quasi-spherical shells around NS magnetospheres should show signs of turbulent velocities with $v_{\text{turb}} \sim v_{\text{conv}} \sim 1000 \text{ km s}^{-1}$.

6 BRIEF SUMMARY OF THE MODEL PREDICTIONS

Lets us summarize the basic properties of the hot magnetospheric shell supported by a propelling NS in circular orbit in a binary system around a Be-star. The model predicts the following observables:

- i) the system emits optically thin multitemperature thermal radiation with the characteristic temperatures above $\sim 10 \text{ keV}$, high plasma densities $\sim 10^{13} \text{ cm}^{-3}$ and EM $\sim 10^{55} \text{ cm}^{-3}$;
- ii) the typical X-ray luminosity of the system is $\sim 10^{33} \text{ erg s}^{-1}$;
- iii) no X-ray pulsations are present and no significant X-ray outbursts are expected in the case of a coplanar circular orbit with the Be-disc;
- iv) the hot shell is convective and turbulent; therefore, the observed X-ray emission lines from the optically thin plasma should be broadened up to $\sim 1000 \text{ km s}^{-1}$;
- v) the typical size of the hot shell is $\sim R_B \lesssim R_\odot$;

- vi) the cold material, such as the Be-disc in the vicinity of the hot shell, should give rise to fluorescent Fe K line;
- vii) the lifetime of an NS in the propeller regime in binaries with long orbital periods can be $\sim 10^6$ yr; hence, such systems should be observable among faint X-ray binaries in the Galaxy.

7 OBSERVED X-RAY PROPERTIES OF γ CAS CAN BE EXPLAINED BY THE PRESENCE OF A PROPELLING NS

We suggest that the low-mass companion of γ Cas can be an NS in the propeller stage. The NS orbits the Be-star in almost circular orbit coplanar with the Be-disc. The Be-disc is contained within the Roche lobe of the Be-star ($\sim 310 R_\odot$),¹ and the NS gravitationally captures matter from the slow Be-disc equatorial wind, which is not limited by the Roche lobe of the Be-star. The scaleheight of the disc outflow in γ Cas is $H_{\text{disc}} = 0.04 R_*$ (Martin et al. 2011), comparable to the aspect ratio of the Bondi radius, which is sufficient to realize the quasi-spherical accretion. The lack of periodic pulsations, as well as properties of the hot thermal plasma measured from the analysis of X-ray observations ($kT_{\text{hot}} \sim 20$ keV and $n_e \sim 10^{13} \text{ cm}^{-3}$, $v_{\text{turb}} \sim 1000 \text{ km s}^{-1}$) (e.g. Lopes de Oliveira, Smith & Motch 2010; Torrejón, Schulz & Nowak 2012; Shrader et al. 2015), which challenge all previously proposed scenarios of X-ray emission from γ Cas (Smith et al. 2016), are naturally expected in a hot magnetospheric shell around a propelling NS (equations 2, 8, 10 and Section 6).

The propeller model explains both the gross physical parameters of hot plasma in γ Cas and matches the properties of its X-ray variability. Indeed, a hot convective shell above the NS magnetosphere should display the time variability in a wide range which depends on the characteristic sound speed, c_s , which is of the order of the free-fall time, t_{ff} . The shortest time-scale is $t_{\text{min}} \sim R_A/c_s \sim R_A/t_{\text{ff}}(R_A) \sim R_A^{3/2}/\sqrt{2GM} \sim$ a few seconds, while the longest time-scale is $t_{\text{max}} \sim R_B/t_{\text{ff}}(R_B) \sim 10^6 [\text{s}](v_0/100 \text{ km s}^{-1})^{-3} \sim$ a few days. These are indeed the typical time-scales of the X-ray variability observed in γ Cas (Lopes de Oliveira et al. 2010).

Typically, Be-type stars display significant time variability in the optical which is produced by changes in the mass-loss rates due to stellar pulsations and possible viscose instabilities in the circumstellar disc (Baade et al. 2016). In complex systems consisting of a pulsating Be-star, decretion Be-disc and an NS, one can expect the characteristic time delay between any changes in the stellar mass-loss rate and Be-disc (usually observed in the optical) and the response of the hot magnetospheric shell (usually observed in the X-rays) to these changes.

The dynamics of discs in binary systems is complicated, especially in the case of large mass ratio, as in the Be+NS case (see, e.g. recent 2D simulations; D’Orazio et al. 2016). In addition, in a Be+NS system, the decretion Be-disc is subjected to a number of perturbations and resonances which truncate the outer disc edge within the Roche lobe of the Be-star (Okazaki & Negueruela 2001). The Roche lobe radius of the NS is

$$R_L(M_X)/a \simeq 0.49 \left(\frac{M_X}{M_{\text{Be}} + M_X} \right)^{1/3} \approx 0.2, \quad (17)$$

where a is the binary semimajor axis, and we used $M_X/M_{\text{Be}} \approx 1/16$ for γ Cas. The characteristic time delay is then determined by the free-fall time inside the NS’s Roche lobe,

$$t_{\text{ff}}(M_X) \approx \sqrt{\frac{R_L^3(M_X)}{2GM_X}} = \frac{P_{\text{orb}}}{2\pi} \sqrt{\frac{R_L(M_X)}{2}} \sqrt{\frac{M_{\text{Be}} + M_X}{M_X}}, \quad (18)$$

where we have used 3D Kepler’s law $\omega_B^2 = G(M_{\text{Be}} + M_X)/a^3$. Plugging values for γ Cas immediately yields $t_{\text{ff}} \sim 40$ d, which is close to the time lag between optical and X-ray variability observed in γ Cas (Motch, Lopes de Oliveira & Smith 2015).

Changes in the absorption column density are also expected due to perturbations in the cold disc and wind induced by the NS on short and long time-scales (Martin et al. 2011; Smith et al. 2012; Hamaguchi et al. 2016). Note also that the single power-law spectrum $P(f) \sim 1/f$ over the wide frequency range from 0.1 to 10^{-4} Hz, as derived for the X-ray time variability in γ Cas (Lopes de Oliveira et al. 2010), is common for accreting X-ray binaries and is thought to arise in turbulent flows beyond the magnetospheric boundary (Revnivtsev et al. 2009).

Future works on hydrodynamic models of Be-stars, their discs and companion NSs will provide more insight into the complex interactions in such systems. The hydrodynamic models show that the shape of the disc is affected by the secondary (Panoglou et al. 2016). Such modelling is required to explain the full range of variability observed in γ Cas and its analogues.

8 γ CAS ANALOGUES IN THE CONTEXT OF EVOLUTION OF MASSIVE BINARIES

All γ Cas-type stars were likely formed through similar evolutionary channels. Consider, for example, the standard evolutionary scenario of a massive binary system with almost equal initial masses $M_p \sim 10\text{--}11 M_\odot$ and $M_s \sim 8 M_\odot$ separated by $20 R_\odot$. After the main-sequence stage, the primary overfills its Roche lobe and transfers a significant amount of matter and angular momentum to the secondary. The hydrogen envelope of the primary is stripped off during the mass transfer to leave the naked helium-rich primary remnant with the mass $M_{\text{He}} \sim 0.1 M_p^{1.4} \simeq 3 M_\odot$. The secondary mass increases up to $M_{\text{Be}} \sim 15 M_\odot$, and the star acquires rapid rotation. Rotating at nearly break-up velocity, the secondary is now observed as an early Be-type star with the surrounding disc. Then, the helium star explodes as an electron-capture SN (ECSN) and produces an NS with mass $M_X \sim 1 M_\odot$ (e.g. Postnov & Yungelson 2014; Moriya & Eldridge 2016). SNe of this type naturally produce NSs with low-velocity kicks (Podsiadlowski et al. 2004; van den Heuvel 2010).

After the ECSN with low kick, the newly born NS remains in the plane of the Be decretion disc and stays in an orbit with low eccentricity $e = (M_{\text{He}} - M_X)/(M_{\text{Be}} + M_X) \sim 0.1$ but moves to a somewhat wider separation (in γ Cas the putative NS is at $\sim 35 R_*$ from the Be-star). Importantly, due to low kick velocity, the NS orbits the Be-star in the Be-disc plane. Be-stars have high dense equatorial winds, the orbital velocity of NS relative to the Be-disc wind can be low, which potentially provides an efficient quasi-spherical accretion. However, the high spin of the young NS inhibits accretion of matter captured from the low-velocity wind of the Be-star. Instead, the NS is embedded in a hot shell, which we presently observe in X-rays.

The hot shell mediates the angular momentum transfer from the NS magnetosphere and can prolong the propeller stage of the NS up

¹ The Be-disc size in γ Cas as measured by the infrared interferometry (Gies et al. 2007) and inferred from emission lines spectroscopy (Hanuschik, Kozok & Kaiser 1988; Dachs, Hummel & Hanuschik 1992) is about two times as small, apparently because these observations sample mostly the densest innermost parts of the disc-like wind outflow; millimetre photometry indeed suggests a larger disc radius, $\sim 33 R_*$, which is close to the Roche lobe size (Waters et al. 1991).

to several 10^5 years or even longer. Therefore, in binaries with long orbital periods, such as γ Cas, the duration of the propeller stage can be comparable to the lifetime of the Be-star (see equation 14). Thus, a sizable fraction of BeXRBs in the propeller stage, i.e. γ Cas analogues, should exist in the Galaxy, as indeed observed.

With time, the NS slows down. With the beginning of accretion, the NS will appear as an X-ray pulsar. It should remain in a circular orbit in the plane of the Be decretion disc and have a relatively large orbital separation. The observational manifestation of such post- γ Cas system is X Per – a slowly rotating X-ray pulsar at the stage of quasi-spherical settling accretion with moderate X-ray luminosity (Lutovinov, Tsygankov & Chernyakova 2012).

9 DISCUSSION AND CONCLUSION

Three often invoked scenarios for the nature of γ Cas are discussed in depth by Smith et al. (2016). Chronologically, the first hypothesis was that of an accreting NS (White et al. 1982). Yet, the improvement in X-ray spectroscopy and timing led to the realization that the X-ray properties of γ Cas are very different from BeXRBs.

Another commonly invoked scenario is the accretion on to a white dwarf (Haberl 1995; Apparao 2002; Hamaguchi et al. 2016). Smith et al. (2016) disfavour the white dwarf hypothesis because of the too high observed X-ray luminosity of γ Cas, which is difficult to achieve without increasing the supply of matter from the Be-disc by discrete ejections. Our estimates show that a propelling magnetic white dwarf as the companion in γ Cas is disfavoured since, with the typical white dwarf magnetic moment of a few $\times 10^{32}$ – 10^{33} G cm³, the magnetospheric radius given the observed low X-ray luminosity would be too large (see equation 7) and gas temperature too low (see equation 10) to match the values derived from X-ray spectroscopy.

The third scenario explaining γ Cas and its analogues does not relate to binarity. Instead, it suggests a magnetic star–disc interaction. In this picture, the entanglement and stretching of magnetic loops from the stellar surface with the disc magnetic field lines lead to reconnection events which accelerate particles. These electron streams bombard the stellar surface. The thermalization leads to the X-ray emission. Albeit some estimates on the thermalization efficiencies are made, this scenario is entirely phenomenological at present and is lacking any predictive power (Smith et al. 2016). Recently Schoeller et al. (2016) attempted to detect magnetic fields in some γ Cas analogues using spectropolarimetric observations, but no evidence for magnetic fields have been found.

In this letter, we propose a novel explanation of the enigmatic class of γ Cas analogues. We conclude that a propelling NS in γ Cas matches X-ray observations very well. The existence of young fast spinning NS companions (propellers) to early Be-stars in circular and coplanar orbits is a natural consequence of the standard evolutionary scenario of massive binary stars and ECSN models. Hence, the synergy between the stellar evolution and accretion theories predicts the existence of γ Cas and its analogues.

ACKNOWLEDGEMENTS

The authors acknowledge ISSI (Bern) for hospitality. We thank the anonymous referee for useful comments and suggestions which helped to improve this letter. The work of KP is supported by RSF grant 16-12-10519. JMT acknowledges the research grant ESP2014-53672-C3-3-P and LO acknowledges the DLR grant 50 OR 1508.

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